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Vertical and Horizontal Integration to Overcome Extreme Operational Challenges for the Achimov Tight, Gas-Condensate Formation

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Abstract

The production focus has shifted from the easy-to-access, shallow, gas-bearing deposits in the Cenomanian and Valanginian of the Urengoyskoye Field to the deeper, tight, gas-condensate formations in the Achimov. Several different operators have started to develop the Achimov formation with different development strategies on over eleven license blocks; however, with the common objective to maximize liquid and gas production from their license. Based on a couple of pilot projects with extensive testing, a unified development plan over the entire Achimov formation had been devised before the development start-up to guarantee hydro-carbon recovery and guide the operators through the development. Due to the enormous challenges encountered in the Achimov formation such as high pressure, low formation quality and deviated well stability challenges, the initial unified development plan foresaw the drilling of simple production pattern with a large amount of vertical wells. However, since the instigation of the unified strategy, the technology has advanced to overcome most of the challenges encountered in the Achimov formation with the potential of improving the sub-optimal, original development plan.

This paper discusses the general challenges of the Achimov development from well construction, production operations to reservoir management encountered by the various operators and attempts to define integrated solutions chains to overcome those. The operational and financial impact of the various technologies of the solution chains is defined and a possible roadmap for field development is devised. Several different operators have started to develop the Achimov formation with different development strategies on over eleven license blocks.

The compelling event

Although the Achimov formation is encountered in nearly the entire West Siberian basin, this paper is referring to the Achimov reservoirs that have been discovered in the Urengoyskoye license area (part of the Greater Urengoy area).

The giant Urengoy gas field is the largest field in Western Siberia – in fact, it is one of the largest gas fields in the world – and from utmost strategic importance for Russia and Europe. With the production commencement in 1978 current annual gas production of the Urengoy field is about 200 10^9 m^3 produced from the shallow Cenomanian deposit and 20 10^9 m^3 produced from Valanginian deposit. The deeper

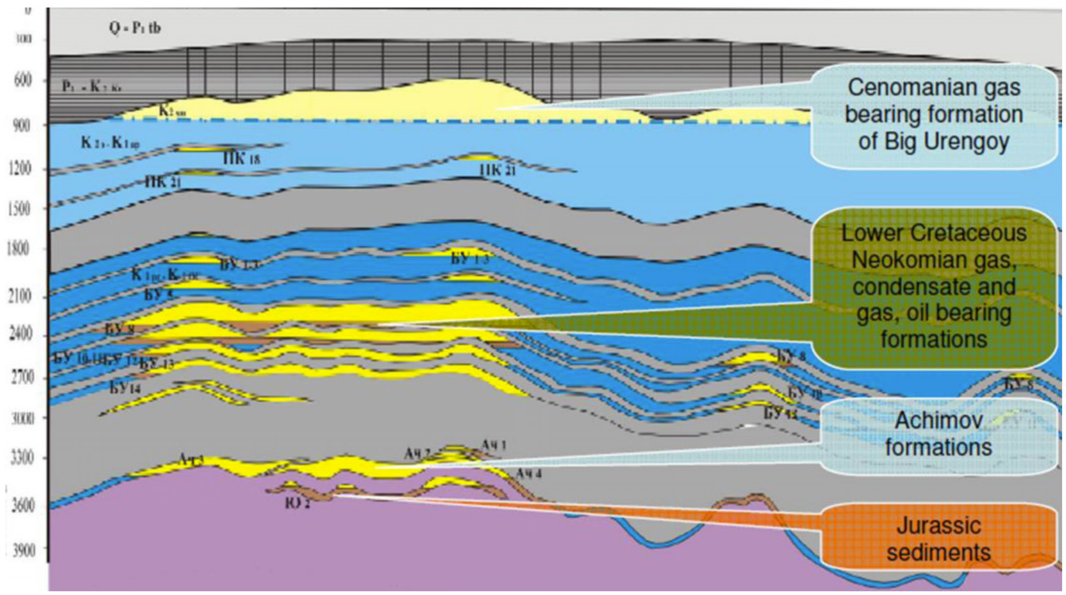


Figure 1—Cross-sectional view of the productive reservoirs in the Urengoy field (Lanchankov)

Achimov deposit is currently under commercial pilot development (Istomin et al.). See Figure 1 for a cross-sectional view of the Urengoy field reservoirs.

Due to the aging giant Cenomanian accumulation, the attention has been shifted to the Achimov deposits in order to compensate eventually decreasing gas delivery rates of the shallower deposits with the additional windfall from the condensate production. Eleven licenses for the Achimov deposits were distributed between several different operators that are expected to reach production capacities by 2016 and full-field development by 2020 with plateau production beyond 2025. For this reason, operators are continuously tripling investments for the Achimov development since 2012 and are ramping up drilling capacities to guarantee their development activities. Research and technology centers have devised around the year 2006 a unification plan (development scheme depicted in Figure 2) that regulates the field development commencement and production rates for the various licenses blocks to counteract potential interference at the boundaries of the blocks.

The unification plan is optimized towards operations by minimizing the technical and project risks while maximizing the recovery. It is focused on drilling vertical (S-shaped type) wells into the Achimov formation and hydraulically fracturing the low-permeable formation for productivity. However, since the inception of the unification plan the technology and its application to challenges has advanced in the way that several of the encountered difficulties can be overcome but delimiting – or even further reducing – the risk and increasing the project value and, most importantly, the recovery. This paper discusses operational and technology strategies with the objective to maximize operational efficiency, gas and liquid production rates and ultimate recoveries.

The Achimov deposits

The Achimov Formation is composed of slope and turbidite facies including reservoir sandstones and siltstones. The Achimov Formation is of Neocomian age (Early Cretaceous) and lies at depths of around 3500 m, which corresponds to the lower part of the oil window (Leonenko). As abnormally high formation pressures are common in most Achimov deposits, the pore pressure is about 200 bar above the common gradient. The sandstones are arkosic, with argillaceous and minor calcite cement; they contain 40 – 55% feldspars, 25 – 40% quartz, and 5 – 20% rock fragments, and grains are commonly poorly rounded (Borodkin). The rocks have undergone strong compaction and diagenetic alterations, primarily quartz overgrowth and calcite dissolution (Leonenko and Karnyushina, 1988).

Reservoir sandstones form multiple lens-like bodies typical for turbidites that have a high risk of discontinuity. In fact, the hydrodynamic connectivity between the bodies is uncertain and can be determined only from data on the extended pilot production (Borodkin et al., 2001).

There are three distinct hydrocarbon-bearing units within the Achimov interval that are commonly indexed as Ach3, Ach4 and Ach5. Some Achimov operators also encountered the Ach6 formation that is potentially oil-bearing. Porosities may vary between the different layers, but are in general moderate up to 18 – 20%. However, permeability is low – and sometimes extremely low – varying from fractions of millidarcies to a few tens of millidarcies. Formations have sandstone beds of several meters thick with shale interbeddings. Even though that a shale layer divides the Ach3 from the Ach4, it is not hydrodynamically isolating the layers over most of the Achimov field as fluid properties and pressure regimes seem to be similar in both layers (hence the reservoirs are commonly referred to as Ach3,4). The Ach5 (and Ach6) is not connected to the shallower Achimov layers.

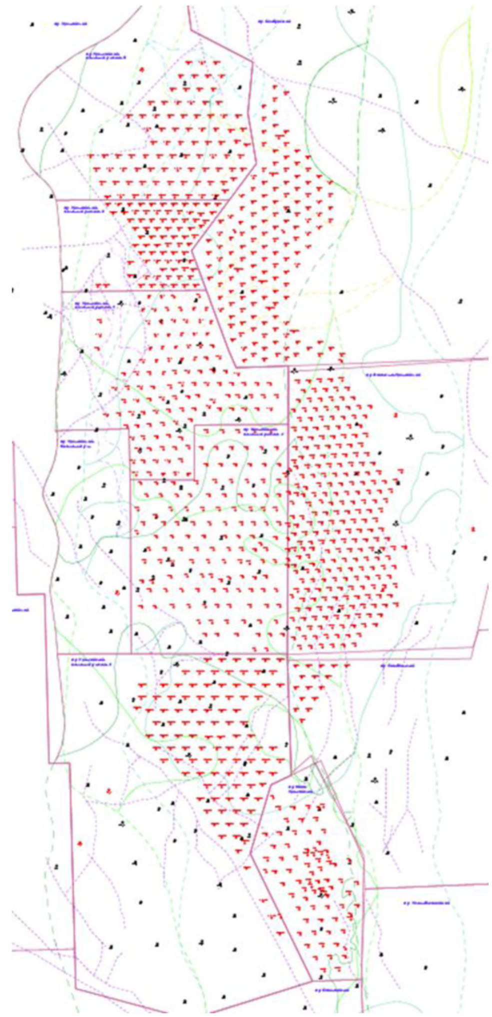


Figure 2—License boundaries of Achimov with approved well head patterns

The Achimov formation is highly overpressured at about 600 bar, which is some 200 bar higher than formations directly above. The reservoir fluids are rich gas-condensates with high condensate content that is in general between 280 to 380 g/m^3 (Descubes et al.). Some exceptional fluid samples from the Achimov formation indicate even higher liquid gas-condensate content of up to 450 g/m^3 making the liquid recovery even more desirable. Notably, oil-rims are also encountered; however, they are not consistently present over the Achimov layers. Some sources (Borodkin) suggest that the gas-condensate is paraffinic and pressure and temperature regimes are favorable for drop-outs.

The Achimov challenges

An attempt to create a comprehensive list of operational and subsurface challenges is listed in this section that does not claim completeness. Moreover, depending on the region in the Achimov formation and the license block some operators encounter those challenges maybe stronger or weaker than others.

Logistics

Hostile operational environment The Urengoyskiy license is located in the Pur area of the Yamal-Nenets Autonomous District located about 80 km south of the Arctic Circle. With all operations close to the Arctic, logistical organization is dependent on short weather windows to transport and relocate heavy equipment. Even though Urengoy area is well developed from almost four decades of activities on the giant Cenemonian gas field, the logistics to develop the Achimov formation represent additional challenges. Drill rigs have to be dimensioned larger to access greater depths, capable to drill complex well trajectories and handle extreme drilling challenges when entering the Achimov formation. Moreover, economic production from the Achimov formation can only be guaranteed with the hydraulic fracturing of the wellbore so fracture-fleets must be available at any time point of the operations.

Alignment of stakeholders The primary goal of the unification plan has been to guarantee the maximum (gas and liquid) recovery from the Achimov formation across all eleven license areas and the initially eight different operating companies. Even though some consolidation to four major license holders has been observed, operators are quite reluctant to share information about their successes with the neighbors in attempt not losing potential advantages over competitors.

Additionally, most of Achimov operators have contracted their operational activities to General contractors which are here mainly drilling contractors, which in turn have sub-contracted essential work to service companies (and so on). This has led to the situation that there is little alignment in the overall objectives since at each step the global objective is diluted with the sub-contractor's interests. In such situation, the necessary technological changes or advances become particularly difficult to implement.

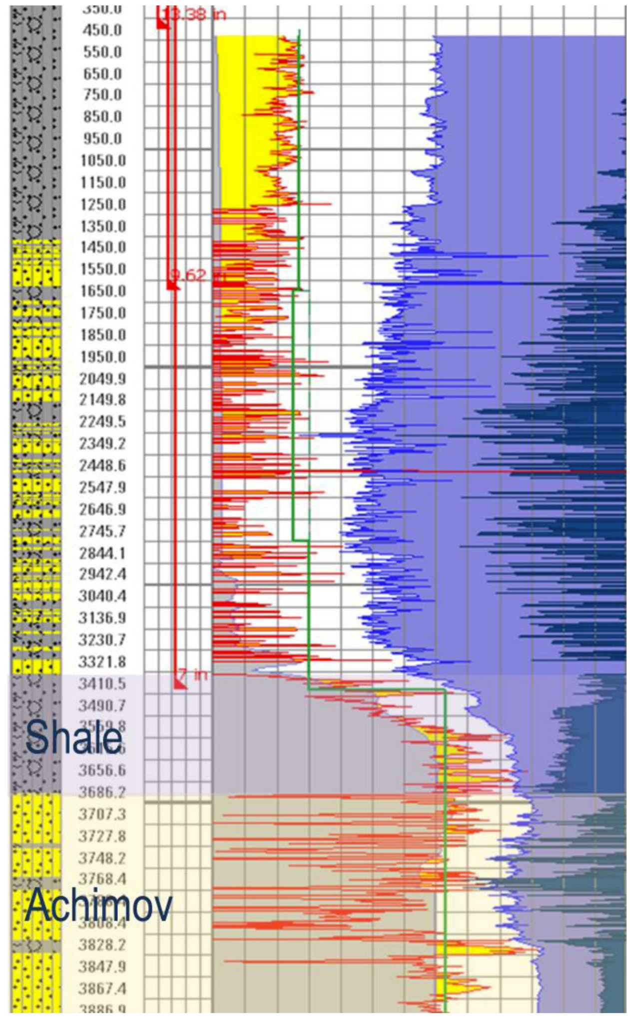


Figure 3—The closing of the safe mud window in front of the Achimov formation

Well construction risk

As mentioned above, the Achimov formation is heavily over-pressured causing nearly unsurmountable operational challenges for complex trajectories. Drillers have to change the mud weight before entering the Achimov to manage the expected pore pressure and avoid gas kicks. On entering the Achimov formation the safe mud window (Figure 3) shrinks leaving only a marginal range to operate. Moreover, depending on the azimuthal direction the mud window closes rendering safe drilling operations impossible for highly deviated or sub-horizontal wells.

As a matter of fact the several attempts to drill a horizontal section into the Ach3,4 without prior geomechanical model failed due to the closing of the safe mud window. In several cases drillers experienced, for example, a gas-kick during pulling-out-of-hole (POOH) and causing a swabbing effect, subsequently the mud weight needed to be increased to contain the kick and as a result the driller encountered mud losses since the Equivalent Circulating Density (ECD) was then above the fracture gradient (described in Tarasov et al.).

This has been a well understood drilling challenge so that the unification plan only accounts for vertical wells to penetrate the Achimov in order to minimize the drilling risk. Moreover, a vertical well would also minimize the completion risk as operations are less complex for the subsequent hydraulic fracturing than for laterals.

Permafrost related challenges are also decupled, due to huge temperature changes during well testing, and drilling and cementing must take this into account.

Extreme reservoir properties

In the nature of a turbidite system, the Achimov formation demonstrates significant heterogeneity of reservoir properties that are difficult to forecast. In fact, due to the scarcity of data, most of them are only poorly understood.

Poor formation quality The Achimov formation is considered by some experts as Unconventional Resource (UR) with permeabilities sometimes well below 1 mD. This might not be seen by standards regarding pure gas production; however, it certainly is unconventional when liquid has to be produced. Permeabilities strongly vary from one reservoir layer to another. For example, some parts of the Ach3,4 display permeability's around 50 to 100 mD, whereas Ach6 layers can be considered as "tight" with extremely poor formation quality.

Heterogeneity Even though that some shale layers in and especially directly above the Achimov formation are reasonably predictable in their thickness and extent enabling correlation to seismic data (Grechneva), reservoir properties within the sand units vary considerably between wells. Regional differences of sometimes of an order of magnitude in the permeabilities can be observed in addition rendering formation quality prediction difficult. Saturation changes can be significant that some operators observe updip "water layers" even though porosities are in the range that would suggest mobility of the water phase above critical saturations (van der Hem).

Compartmentalization and connectivity In general, the Achimov formation constitutes of clinoforms (each representing a cyclic sedimentary event) that compartmentalize the formation in lateral direction. Some operators have attempted to map sand bodies using seismic and dynamic data (Grechneva) with limit success as the predictability for infill wells was not significantly improved.

Limited fracture growth Hydraulic fracturing has been extensively tested by all operators with reasonable success to increase productivity. Even though there are limitations to use monitoring wells for micro-seismic due to the current low well density, hydraulic fracture monitoring has been performed using surface geophones. Those measurements suggest limited lateral fracture growth for the Ach5 formation. It has also been observed that the fracture propagation direction can change away from the wellbore (and flip) leaving a significant part of the fracture unproductive. Both observations indicate either the presence of extreme reservoir heterogeneity or an isotropic (relaxed) stress regime that allows the fracture to suddenly change the direction during hydraulic fracturing operations. It also has to be noted that in most of the analyzed cases resides to a larger extent the ambiguity in a possible fracture growth from the Ach5 into the Ach3,4.

Uncertain production environment

The Achimov operators are closely monitoring the production behavior – especially the gas-condensate ratio (CGR), as a comprehensive understanding of the drainage behavior of the gas condensate is essential for maximizing liquid and gas recovery (Afanasyev et al.). However, several phenomena such as strongly fluctuating CGR and uncorrelated CGRs to neighboring wells (see below in Figure 4) have been observed that do not allow conclusively deriving optimum production strategies. This has been further affected due to poor zonal isolation between Ach 3,4 and Ach5 generating crossflows between these formations. Operator that decided to test the well and run production logging tools, have observed crossflow.

Reduced well productivity The dew point pressures of the gas condensate in the Achimov formation are about 20 to 50% below the initial reservoir pressure. Due to poor formation quality, the producers are very likely to draw down below the dew point right from the production start-up causing the liquid to drop out and triggering the well documented effect of gas condensate banking. With the decreasing productivity from the condensate bank and liquid formation in the wellbore itself – liquid fallback – the gas production is jeopardized with the well potentially shutting-in.

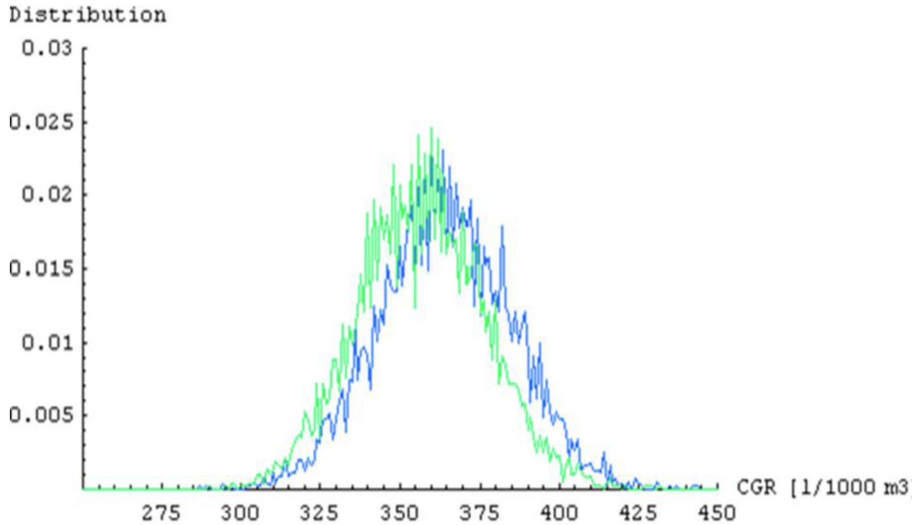


Figure 4—Examples of measured CGR distributions for two different, neighboring wells from the Achimov formation (Ach3,4)

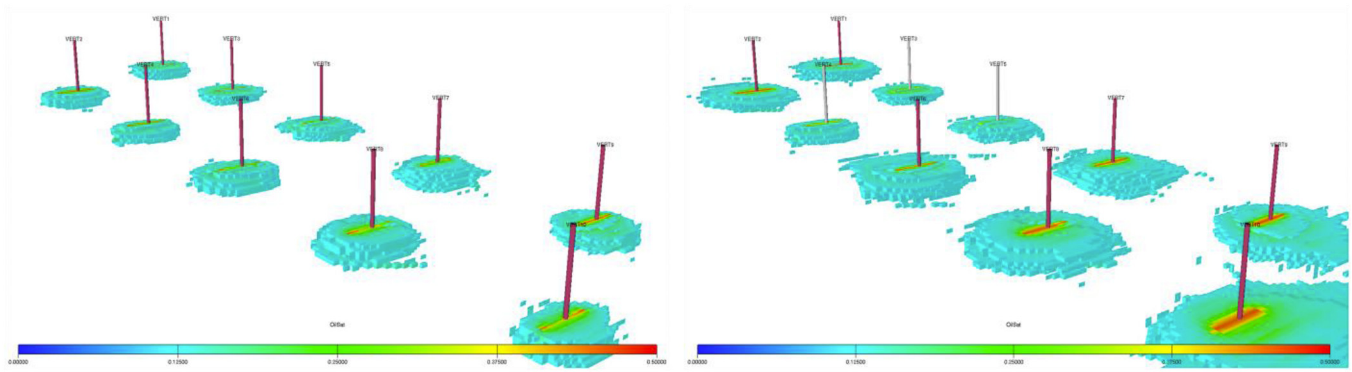


Figure 5a and Figure 5b—Sector model with average Achimov properties showing the liquid distribution around ten hydraulically fractured production wells showing gas condensate banking after 1 year and 5 years, respectively

Figure 5 shows the liquid drop out around ten vertical, hydraulically fractured production wells after the first year (Figure 5a) and after the fifth year (Figure 5b). The model is a sector with rock and fluid properties that can be observed in the Ach3,4 and Ach5. For accurate production behavior modeling, the hydraulic fractures are explicitly modeled with all correct wellbore fluid behavior included (such as liquid fallback, friction and turbulence effects for example). As can be seen, the gas condensate bank establishes early in the production even within the first year of production and increases with time as the reservoir pressure drops away from the wellbore (Figure 5b). In this realization, three out of the ten wells, which are completed in poor formation quality, cease production (Vert3, Vert4, Vert5 depicted in grey compared to the red active producers) within the first five years due to extremely low productivity and liquid fallback. Extrapolating the model to the full-field development about (20 to) 30% of the producers will cease production within the first five years once the full development – and depletion – is in progress and if no mitigation strategies are taken.

Velocity stripping Production tests on Ach3,4 wells indicate also the influence of non-Darcy effects on the production behavior such as turbulent flow and velocity stripping negatively and positively impacting the well productivity, respectively. However, studies suggest that production at high flow velocities does not have significant impact on the well productivity for Achimov wells, which is especially true when the wells are hydraulically fractured (Descubes et al.).

Compartmentalization and fluid distribution Due to the geological environment the Achimov layers are compartmentalized. This can be observed from the varying PVT properties that are encountered throughout the formation. Some operators find completely different hydrocarbons in place than their neighbors. Oil-rims – and even oil pools – are tested where the dew point must be right at the reservoir pressure rather than well above as observed generally. Attempts to map the liquid property distribution have not been successful with the limited and ambiguous amount of data available.

Affinity to paraffin precipitation During the operation of oil-producing wells intensive paraffin and/or paraffin-hydrate precipitation is estimated to take place in the production tubing and may also occur at the field treatment system at the surface facilities for Achimov gases (Ignatyev at al.).

Completion strategy The completion strategy is different between operators. Some are basing their production strategy on slotted uncemented liners and others on cemented liners, which are perforated over the producing interval.

Back-allocation and reserves accounting Most operators are considering simple completion technologies that will most likely involve either unintentional or intentional commingling of different productive horizons. The former could be the situation of fracture growth out of Ach5 and producing from Ach3,4 with the Ach5 jointly. This has been observed by most of the operators that have fractured both Ach3,4 and Ach5. The latter could be the commingling completion strategy for the Ach6 together with more productive layers for economic reasons. Back-allocation to the various horizons will be extremely difficult due to the reservoir and fluid effects described before. Hence, commingling will jeopardizing the reserves accounting and will render optimization of the liquid and gas recovery impossible.

Extract of the problem

In one way or the other, the discussed Achimov challenges represent either operational or technical risk. These risks might be mitigated in various processes such as in equipment or technology optimization, operating procedures and measurement-control optimization – all centered on the objectives to:

- gain operational and technological efficiency,
- maximize gas and liquid production rates and,
- maximize gas and liquid recoveries.

One example of an optimization loop for the Achimov development would be to create an exact model of the asset, feed this model with the (streaming) information from the asset, calibrate and forecast optimization strategy, implement and monitor in the field development (and feedback). Such "looping" process maximizes the knowledge gain and will allow operators reacting to sub-optimal conditions or even allow preventing them. However, since the challenges are fundamentally linked in depth and in width, the solution(s) have to be vertically and horizontally integrated to tackle them all.

The horizontal well

The strategy to develop the Achimov should entail hydraulically fractured, long sub-horizontal wells or even Maximum Reservoir Contact (MRC) wells rather than vertical wells. It is well established that the larger the exposure of the wellbore to the reservoir the higher is the well productivity. This is especially true for low permeable, tight formations where the economic factor exaggerates the impact of low production rates. Studies on the well productivity in tight gas-condensate reservoirs have demonstrated that horizontal wells (Jamiolahmady, et al.) and horizontal, hydraulically fractured wells reduce pressure drop and improve well productivity (Hashemi, Gringarten). Recent case studies (for example Al-anazi, et al.) successfully prove the superiority in the productivity of multi-stage fractured, long horizontal wells for tight gas-condensate reservoirs.

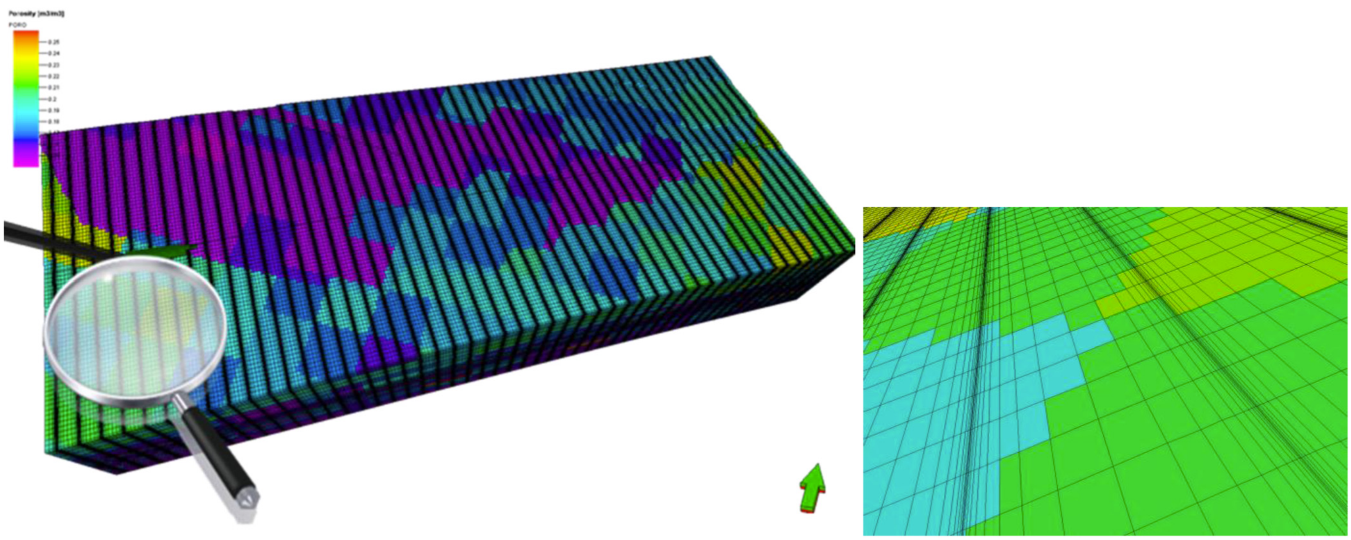


Figure 6—3D view of the sector model with a zoom showing the Tartan gridding with logarithmic grid block sizes around the various fracture cells

The unification plan utilized vertical wells as a mean to reduce the operational risk such as from drilling and completion activities. This automatically imposes limitations on the production and reservoir management, which might create sub-optimal economic conditions. Rather driving the development plan from the operational point of view, the strategy for tight and complex formations has to be derived from the optimum production and recovery solution first and then strategies for operational activities have to be developed to overcome the challenges there. This might not be a guarantee for success; however, the author believes that technology and processes, as well as the experience and data obtained during the pilot phase, allowed already the advance since the inception of the unification plan and a "bottom-up" approach to Achimov challenges is feasible and should drive the development plan. Also, horizontal or MRC wells are mitigating the geological risk of compartmentalization and connectivity that might have deep impact on the well efficiency and productivity. Obviously, the compelling argument for complex wellbores has to be derived with economics.

The Achimov sector model

A numerical model has been created that covers the area of ten vertical infill wells of a typical Achimov environment containing the Ach3,4 and Ach5 formations. The geological and petrophysical data captured in the sector model reflect the general range of Achimov reservoir properties. Dynamic rock and PVT properties for the Ach3,4 and Ach5 have been taken from a randomly chosen part of the field and represent averages encountered in the field.

The model attempts to correctly capture physical representations of near and in-situ wellbore effects. The model itself utilizes specialized gridding techniques, so-called Tartan grid, to allow explicit fracture modeling (Figure 6) and study condensate banking and non-Darcy flow both around and in the fractures and wellbores. Most importantly for numerical sensitivities, the gridding technique offers the possibility to place wells, either vertical or sub-horizontal, with any freedom on the location of the well itself and the various hydraulic fractures. The wellbore uses segmented fluid flow calculations to account for liquid redistribution, fallback, and friction losses.

The sector model has been populated with a variety of different wellbores that are listed in Table 1. All three well types, the vertical wells, the short and long sub-horizontal wells, are penetrating the Ach3,4 and Ach5 and produce commingled. The hydraulic fractures are also penetrating both formations. Different fracture density scenarios for the sub-horizontal and MRC wells have been modeled to study the dependence of the liquid recovery on the amount of multi-stage fractures. The sector model contains either ten vertical wells, depending on the well length two to three sub-horizontal wells or a single MRC well.

Table 1—The three different well scenarios in the sector model

	Vertical (S-shape)	Horizontal well	MRC well
Reservoir penetration	< 50 m	500 - 1500 m	4000 m
Fracture stages	1 - 3	3 - 6	20+
Production tubing	3.5″	3.5″ - 4.5″	5.5″
Logistical risk	low	low	high
Drilling / completion risk	low	moderate	high
Reservoir connectivity	low	moderate	very high
Geological risk	high	moderate	moderate
Production (gas + liquid)	1x	> 3x	> 10x
Recovery (gas/liquid)	low/moderate	moderate/moderate	moderate/high
Individual well costs	$	$$	$$$$
Development costs	$$$$	$$	$$

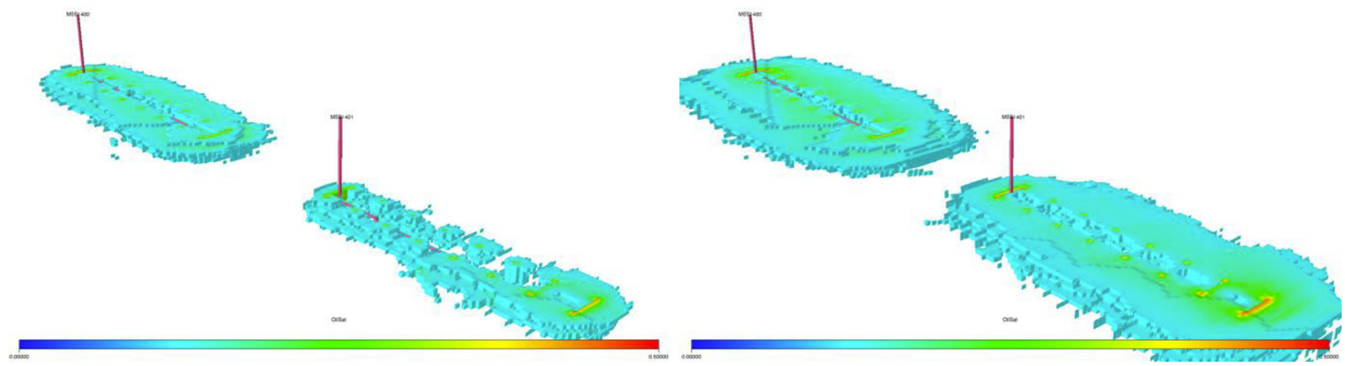


Figure 7a and Figure 7b—Sector model with average Achimov properties showing the liquid distribution around two hydraulically fractured horizontal production wells showing gas condensate banking after 1 year and 5 years, respectively

In order to allow direct comparison between the different well scenarios, regardless of the well productivities the overall gas production rate for the sector model has been kept the same throughout the sensitivities. This in fact is a realistic assumption from the operational point of view as production limits or guide rates exist in the unification plan.

The Figure 7 shows two horizontal wells of about 1000 m lengths with the condensate bank around the wellbore after one and five years, Figure 7a and b respectively. As can be seen, the liquid saturation is well established after the first year in both laterals; however, it is more developed around the well that is completed in the lower permeable part of the reservoir. This is due to the fact that the well in the low permeable zone quickly drops below the dew point and the condensate drops out earlier and becomes more widespread. After five years though, the condensate bank is larger around the lateral in the higher permeable zone. This well is the main contributor to the production in the sector model since productivities of the lateral in the low permeable zone have significantly decreased due to the condensate bank around it.

A similar behavior can be observed in the case of the 4-km long, stage-fractured, horizontal (MRC) well depicted in Figure 8; however there, the condensate build-up around the wellbore is more uniform over time. The condensate bank and the induced reduced productivity are somewhat regulating the inflow into the wellbore so that the condensate bank is more homogeneous.

The major difference of the horizontal well scenarios from above (Figure 7 and Figure 8) to the vertical wells scenario discussed in Figure 5 is that in all sensitivities the horizontal wells survive the first five years of their production. The length of the horizontal well does act as mitigation strategy for lowest permeable reservoir regions allowing low productive parts of the wellbore to be carried through the well life by the productive parts. This is also true – and sensitivities have shown that – for structural risk in

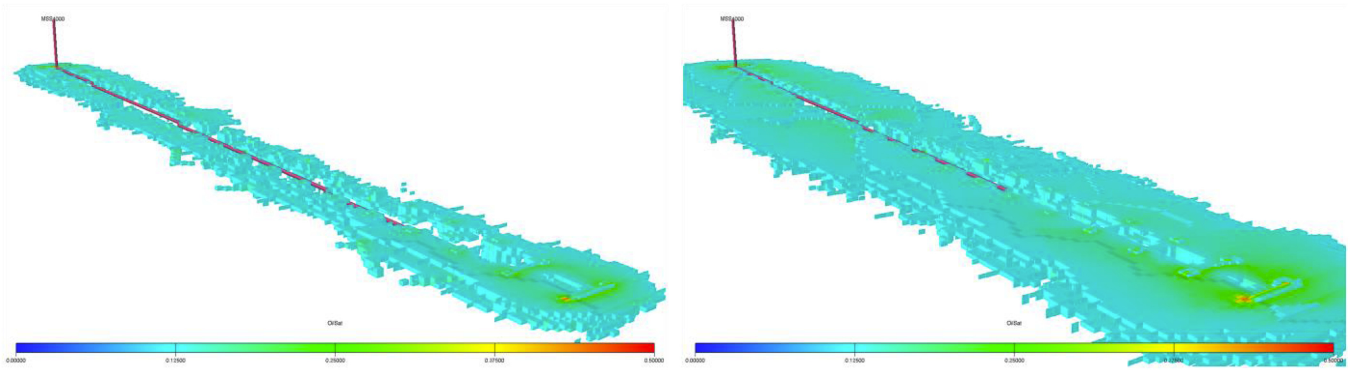


Figure 8a and Figure 8b—Sector model with average Achimov properties showing the liquid distribution around a hydraulically fractured horizontal production wells (or MRC) showing gas condensate banking after 1 year and 5 years, respectively

the way that long laterals are more likely to produce from several reservoir compartments, withdrawing from a larger drainage area and reducing the probability of producing from an isolated compartment alone.

It has also been noted that the optimization of the production tubing size has considerable impact on the production rate of the longer wellbores than shorter laterals. The balance to control liquid fallback and maintain high production rates is critical for MRC wells. Sensitivities have shown that a 5½″-production tubing is required for the MRC well rather the slimmer 3½″ that suffice less productive wellbores. However, the larger production tubing would require major changes in the drilling operations (rig dimensions and logistics) that traditionally are geared in the area of the field towards smaller diameters. Intelligent completions shall also be used, including multilaterals, downhole flow control valves and zonal isolation packers.

Economics

The various sensitivities with the sector model have been used for simple net-present-value calculations using standard economic parameters applicable to the Achimov development. Table 1 also shows some economic assumptions that have been used. For example the construction of a vertical well is substantially cheaper than horizontal wells or even MRC wells. Long horizontal wells will take significantly more time to drill than vertical wells and will also have an extremely more complex completion technology (such as multi-stage fracturing technology, pressure and production rate measuring devices, active control devices, etc.) installed. These complex wells will therefore be three to six-times more expensive than vertical wells. However, the overall field development costs will be less with the long horizontal wells since only few wells will be drilled and those are more than compensating the well investment. The economics only considers the sub-surface investment and not any cost associated to well pad and facility construction that, if accounted for, will have an additional positive economic impact on the long horizontal wells.

Figure 9 shows the cumulative cashflow for various well scenarios using only the gas production for economic calculations. The blue line, for example, shows the cashflow for ten vertical wells. Even though some Achimov operators can drill and complete vertical wells cheaper, the total investment costs for the purpose of this paper have been estimated to more than 150 MMUS$. This investment cannot be compensated by the gas production alone as the cumulative cashflow is still negative after ten years of production. The horizontal wells, which have a smaller overall investment upfront and higher total gas production rates, will pay back the investment with the gas production alone – after around four years. The investment of the vertical wells will be certainly paid back considering gas and liquid production (Figure 10). However, the difference of the long horizontal or MRC wells to the vertical wells increases as they horizontal wells also optimize the liquid production rate. The cashflow difference after ten years is in excess of 100 MMUS$.

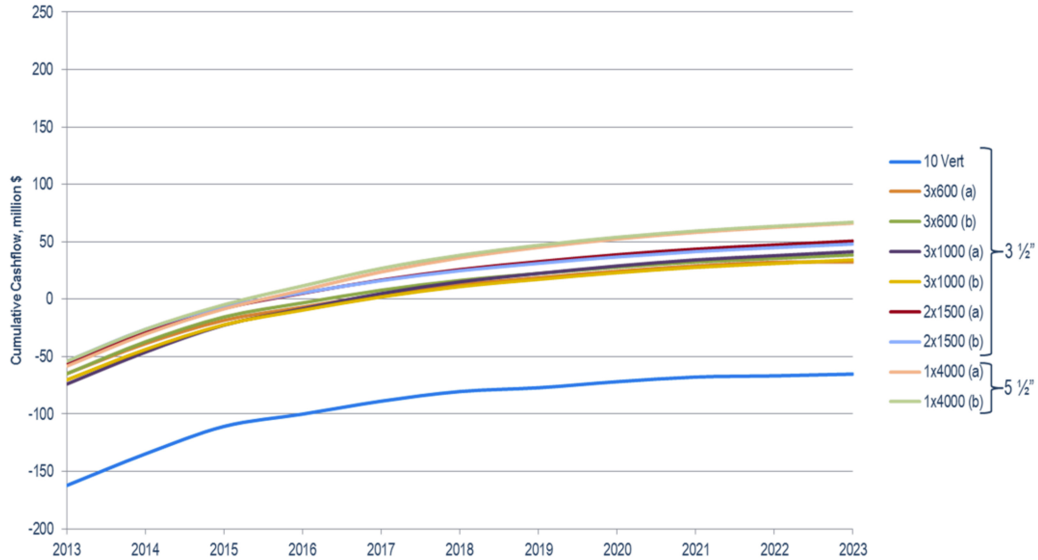


Figure 9—**Cumulative cash flow of various well scenarios in the sector model using only gas production for simplified economics (ten vertical, three 600-m laterals, three 1000-m laterals, two 1500-m laterals, one MRC wells with different fracture densities (a, b))**

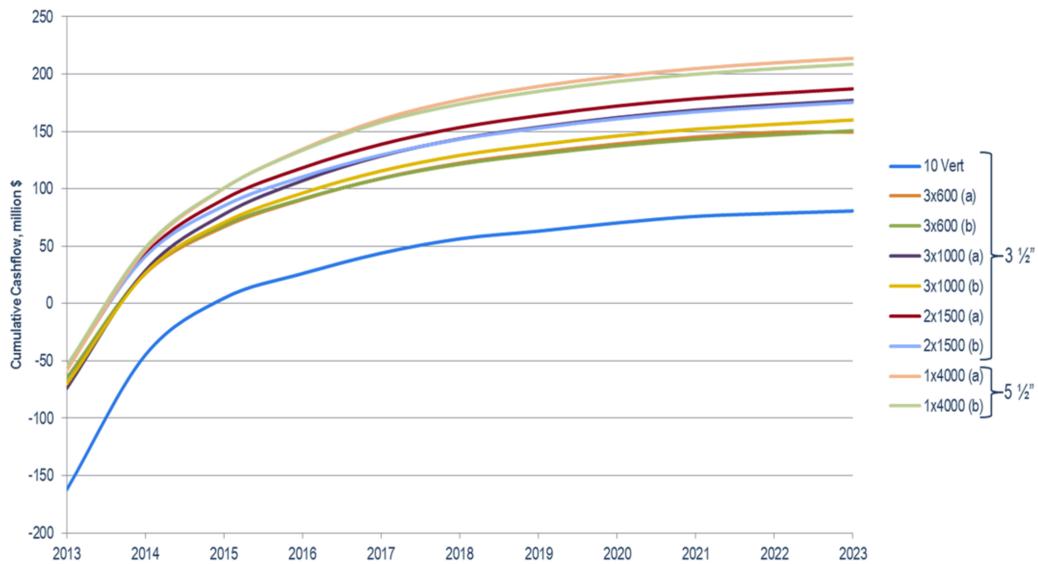


Figure 10—**Cumulative cash flow of various well scenarios in the sector model using gas and liquid production for simplified economics**

The economics have proved that the main production objective for the Achimov field has to be maximizing the condensate recovery and reducing the overall investment. This can only be achieved by changing the current development and using horizontal and/or MRC wells. Additional benefits might arise from the optimization of the surface installations with the lower amount of production wells and well pads. Also, those wells would mitigate geological and structural risk reducing the potential production cessation.

Yet, long horizontal, multi-stage fractured wells will certainly increase the operational risk.

Risk assessment

A risk assessment on technical, operational and logistical activities has been performed to exhaustively explore the Achimov challenges that negatively impact the success of the various well types. A common risk matrix (depicted in Figure 11) has been used to quantify the different types of risks and allow comparison of different operational or technical activities (such as drilling and geological for example).

Any activity can be grouped in the risk matrix by its potential negative outcome for its severity and likelihood of its appearance. The former could be either based on the damage to life or the costs of remedial action (for example the costs of 1 MMUS$ for remedial actions would be “catastrophic” on the severity axis). The latter can range from rare (> years) to very often occurance (days). The combination of the severity and likelihood will define the risk and the resulting action. If the risk is too high (black region in the risk matrix in Figure 11), the operator will either not embark on these activities or has to implement mitigation and prevention strategies to lower the risk to acceptable levels. The conclusions from the risk matrix have been recorded in a risk register where also potential mitigation and prevention strategies are defined.

Based on the challenges that have been already discussed in this paper, some examples of the argumentation chain on the risk and mitigation is given in the following paragraphs.

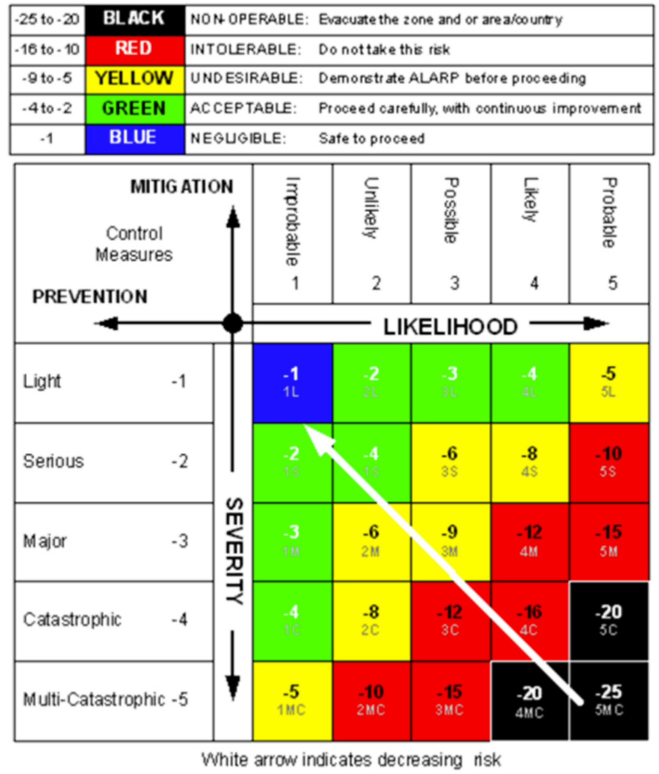


Figure 11—Common risk matrix with color code

Geological risk The turbidite environment of the Achimov formation presents extreme risk for vertical wells due to compartmentalization and the difficulties to predict low productivity zones. Simulation has demonstrated, as discussed earlier, that both can cause premature and early production cessation rendering operations subeconomic. Mitigation strategies might encompass acquisition of a high-resolution seismic data, extensive logging/coring in new wells and detailed geological analysis and modeling to capture the geological features detrimental to the productivity and recovery. The placement of the wells might be directly influenced resulting in a more dynamic development strategy that “searches” for sweet spots.

Besides, (from a stochastic point of view) an additional mitigation option might be to drill and complete horizontal wells as long as possible to overcome potential compartmentalization and/or low productive zones.

Production risk Obviously, horizontal wells have a larger reservoir contact than vertical wells and, hence, are the mitigation strategy for uneconomic production rates of vertical wells that might be completed in low permeable reservoir zones. Still, there is a need to further reduce the risk of low productive vertical and horizontal wells and maximize the reservoir contact with hydraulic fracturing.

Completion risk As already observed in some parts of the Achimov reservoirs, hydraulic fracturing bares in itself higher risk as the fracture direction and propagation might be changing. This might reduce the effectiveness of the fractures and increase the risk of sub-economic stimulation activities. Moreover, the longer the horizontal well is, the more complex the completion operations become. For example drag and torque might delimit operations to a maximum completion length. Or, fracturing and well cleaning operations might be rendered impossible due to limited accessibility of the lateral. Mitigation strategies might entail a drilling trajectory that considers the optimum placement and cleaning of the completion upfront, or the application of latest technology advances on hydraulic fracturing and testing equipment, or the monitoring of fracturing operations with specialized wellbore measurements and micro-seismic, or all techniques at the same time.

Drilling risk The drilling risk into the Achimov formation is highest for all complex well trajectories because a thin operational line has to be managed. The mitigation strategies to overcome the drilling challenges and allow constructing horizontal wellbores are numerous. Those could be:

- The design of the well trajectory based on a thorough understanding of the geomechanical environment. The real-time analysis of the rock properties (strength, stress regime, petrophysical properties etc.) will allow to guide drilling operations and optimize the well path.
- The geomechanical analysis will also guide the mud engineers to manufacture a drilling fluid that provides the exact densities to drill through the high-pressure zones in the Achimov. The mud can be engineered with treated micronized weighting agents to reduce the risk of static and dynamic sag; reduce the ECD in the narrow mud weight windows; reduce swab, surge, break circulation; and reduce the risk of formation damage; etc. Moreover, the mud system can be designed to reduce drag and torque for drilling and completion activities mitigating the risk of long and complex completions. Conversely, Diesel based or oil base mud will also increase ecological risk.
- Real-time logging in general and the in-time model update will support the decision-making process for all drilling, completion and stimulation activities.

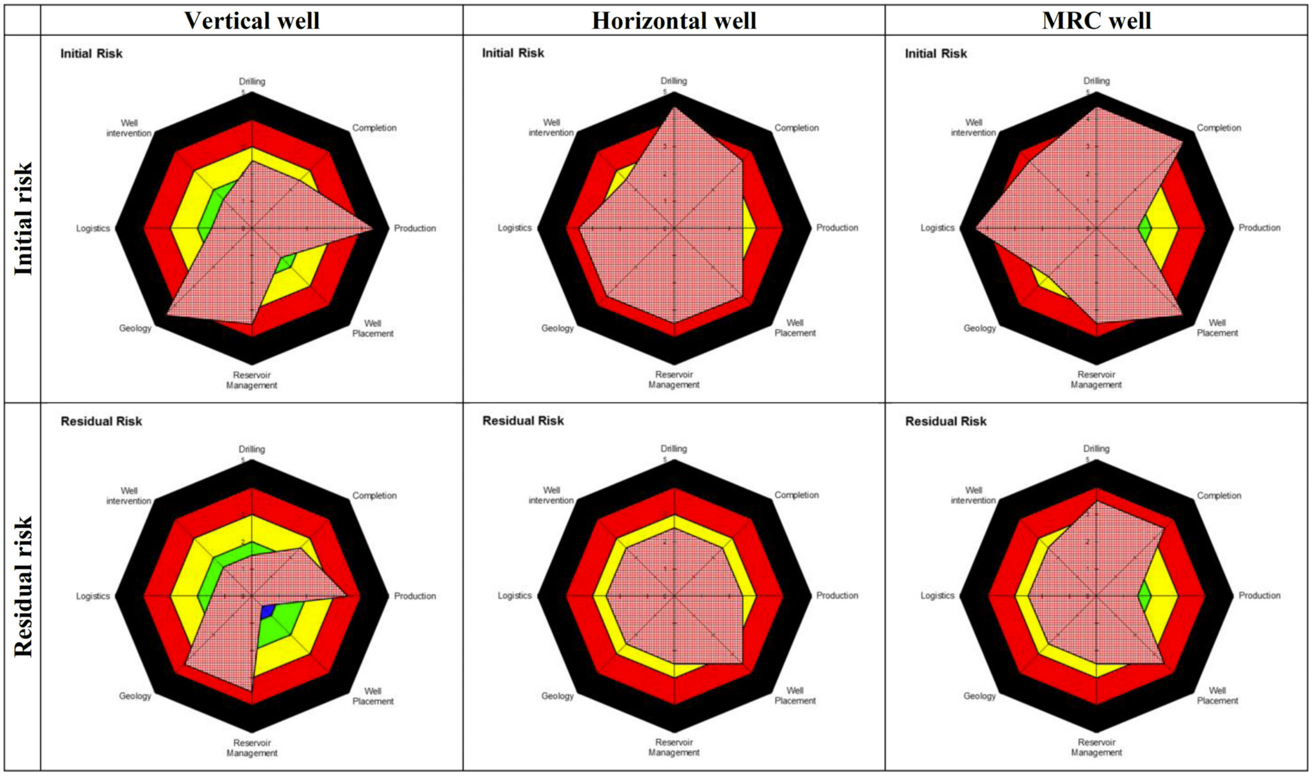
Reservoir management risk In order to guarantee production optimization on a well, reservoir and field basis, measurement devices in the borehole and at the surface have to be installed so that the learning curve on the reservoir behavior can be established. Proactive devices in the completion and at the surface have to enrich and support the decision-making process. Those proactive devices should also provide the operator the possibility to act to unforeseen changes in the production behavior and implement the optimum mitigation strategies for the reservoir and wellbore. Only then the gas and liquid recovery can be maximized. The implementation of the "intelligent" or "smart" processes has to have several optimization loops – guiding the production strategy on the completion level, determining and optimizing the fluid flow on the wellbore level, and defining the optimum overall production strategy for the surface facilities on an asset level.

The concentrated summary of the risk register for the three well types is depicted in Table 2 in the form of a risk rose. The upper part shows the initial risk for eight technical, operational and logistical activities of which some have been discussed above. The lower part of the table shows the residual risk that remains after the implementation of mitigation and prevention strategies. It is obviously the goal to reduce the risk; however, not necessarily all strategies will do so. Nevertheless, if activities are in the non-operable part of the risk matrix, the mitigation and prevention has to shift the activity to at least intolerable risk, where through special and strictly monitored procedures operations can be executed.

It has to be noted that the initial risk for the production and geological activities is highest and are in non-operable risk regions. This means that simple vertical wells – without mitigation and prevention strategies such as for example an accurate sedimentological and structural model, which can be used for well placement, and hydraulic fracturing to maximize the exposure of the wellbore with the reservoir – will exhibit low or marginal productivity (and will be most likely sub-economic in the long term).

The horizontal wells have highest risk in the drilling activities that with the correct procedures can be significantly reduced to undesirable risk. The MRC bares the highest risk in drilling, completion, well placement and logistics. The logistical activities are high risk because of changing from practiced to a new drilling and completion standard. Due to the highest productivity, the larger production tubing necessitates the change of the rig, the casing and the drilling equipment, which close to the Arctic Circle represents biggest challenges, mainly related to the weight and size of such rig, and the rig pad must also be

Table 2—The risk roses for the three well types for the initial state and the mitigated, residual risk



re-enforced. Definitively, the mitigation and prevention techniques can move the risk away from non-operable risk.

The risk management exercise and the creation of the risk register has shown that the various mitigation and prevention strategies are not only reducing the risk on several different activities (or technical domains), but also require the interaction to other technologies and processes to maximize their impact. For example, the geomechanical model of the Achimov will improve its predictability with the data-at-hand and can support the decision-making process for drillers, mud engineers and completion engineers in real-time. The geomechanical laboratory investigations will have direct impact on the mud system too and will guide through the design of the completion and hydraulic fracturing activities. Together with micro-seismic the geomechanical analysis will establish the learning curve for hydraulic fracturing activities and will define operational procedures for drilling and production activities. The reservoir and production management will have to incorporate the geomechanical model into their models to accurately predict production performance changes, potential subsidence; and so on. . .

Similarly, the investigation in the PVT properties and the analysis of the fluid behavior in the reservoir, in the wellbore and in the facilities will enable an entire chain of solutions that are dedicated to maximizing the gas and liquid production rates and recoveries. The mapping of the fluid properties based on an extensive data gathering exercise on fluid property measurements, for example, will provide additional information for the geological model on compartmentalization and stratification. As a result, the risk on well placement will be significantly reduced and higher productive wells will be completed as potentially low productive or compartmentalized areas in the Achimov formation can be avoided or mitigated with an optimized well penetration strategy. The improved understanding on the PVT properties, and its changes over time, will also help in the production optimization to mitigate (or delay) condensate banking and liquid fallback. Paraffin drop out of the gas and liquid phases might be minimized. However, the mitigation of the production and reservoir management challenges cannot be solved by simply looking at single activities. In fact, asset optimization for recoveries and production rates will only be possible through establishing the learning on how to handle the various fluid properties on an asset level with loops on well basis, reservoir basis and downstream basis – calling for an integrated asset model.

The risk analysis demonstrates that overall solutions of Achimov challenges should be horizontally integrated over all technical domains as all activities are to some extent linked in the optimization process and most solutions would not be successfully implemented without others. The vertical integration within the technical domains through specific data gathering strategies (laboratory, in-situ, and reservoir) should establish the in-depth knowledge on the various activities. This is necessary to support the decision-making process in the long-term over the field life as well as in the short-term such as for real-time support for operational activities.

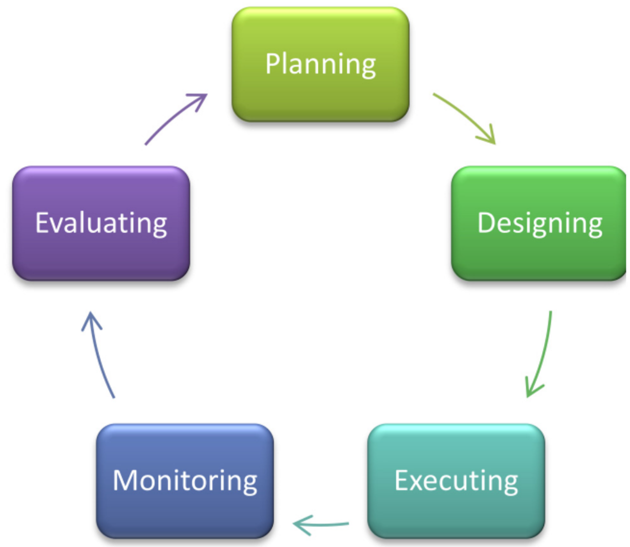


Figure 12—Traditional project management approach for well construction activities with the various stages that will ascertain the establishing of the learning curve

Solutions strategies

The proposed techniques in this section are bottom-up approaches that have the primary objectives to maximize both the gas and liquid production rates and recoveries while honoring the preconceived constraints. The necessary processes and technologies to achieve the objectives are defined, implemented and over time optimized – this is called "establishing the learning curve". The secondary objectives are to optimize those constraints (with growing knowledge on technical, technological, practical processes) and reduce the limitations. The thorough risk assessment of the various processes and technologies will drive the engineering work to ascertain a smooth learning curve that originates from proactiveness rather than an erratic, unpredictable curve from reactiveness.

Well construction integration

All activities have to guarantee safe operations under all circumstances and try to avoid non-operable risk. So any activity to achieve the primary objective of production rate and recovery cannot jeopardize the overall operation. Even though that many operators' strategies are driven towards "do-it-right-the-first-time", it would be perilous to assume that highly complex and difficult processes required for the Achimov bottom-up approach will be successful straightaway. The training of the people, the preparation and refinement of the technology and the definition of workable standards require a step-wise approach that enables the positive development towards fulfilling the secondary objectives. The learning curve is then the evolution of the engineering assessment that iterates in the project management loop depicted in Figure 12. The construction of the (horizontal) well will be designed and executed with mechanisms in place to allow measuring the successes and failures. The results are then evaluated, conclusion drawn and new, improved processes, technologies or standards implemented for the next well (activities).

As highlighted in the risk assessment described earlier, the integration for drilling and completing a horizontal well in the Achimov formation has to entail geomechanical assessment, laboratory analysis, drilling engineering, mud engineering, definition of operational procedures, data gathering strategies for real-time decision-making processes and stake holder alignment. The primary objective is still to guarantee maximum production rates and recovery, but then again geological assessment, well placement and reservoir management conclusions will obviously influence – and possibly drive – the well construction operations. The deliverables from this process will range from the drilling trajectory to the definition of the bottom-hole assembly (BHA), operational procedures to minimize the risk for gas kicks and mud losses, the mud properties and the measurements in the BHA to allow proactive drilling operations.

Figure 13 shows the drilling curve of the horizontal section of various Achimov wells versus time. Two attempts to complete a horizontal well (green and red) in the Ach3,4 and Ach5 failed due to extreme challenges encountered during drilling activities that could not be overcome. In fact, none of those two wellbores achieved completing in the Ach5 reservoir target. Obviously, the reduced wellbores exhibited poor production performance. The blue lines in this plot represent the first well that has been engineered with integrating drilling activities, mud design, and BHA design on the basis of the geomechanical model (three-dimensional mechanical earth model) and extensive laboratory measurements. The design of the BHA included an extensive logging while drilling suite that was able to support the decision-making process in real-time. This allowed changing operational parameters on the fly improving the rate of penetration, allowed determining the optimum casing shoe depth (which was key for safe drilling operations in the high-pressured Achimov formation) and enabling smooth completion operations. As a result, the actual drilling performance (solid) for the horizontal well could be improved by a factor of two compared to the planned drilling curve (dashed).

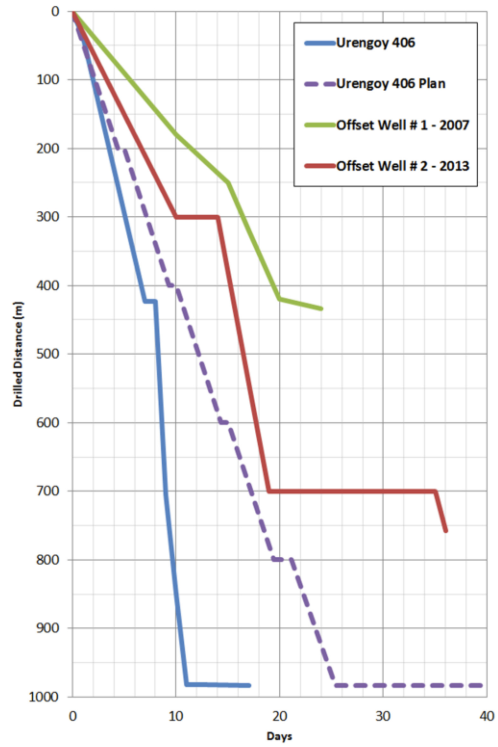


Figure 13—Example of a successful construction of a horizontal well in the Ach3,4 and Ach5 establishing the learning curve through total integration – from engineering to stakeholder alignment (depths are for the length of the laterals)

Most significantly, the engineering integration of all activities automatically facilitated stakeholder alignment that was unprecedented to operation before. Preserving the primary objective – the productivity and recovery – as the main target, operator, drilling contractor, service companies and sub-contractors needed to adhere to the pre-defined processes, technologies and activities (Oil & Gas Eurasia).

Identification of key technologies and their integration

In order to overcome the Achimov challenges in general, the implemented technologies have to support the rapid decision-making process in all stages and guarantee establishing the learning. Also specific technical solutions have to be introduced to shift the operational constraints and allowing risk mitigation.

Data gathering is the key for decision-making support in real-time or in-time or over the life span of the field. Enhanced measurement while drilling tools during the well construction operations, for example, will support the drilling and completion activities; streaming data from completions, wells and facilities will enable asset optimization procedures for reservoir and production management. Laboratory measurements on cores will set the foundation for geomechanical drilling and completion support. Microseismic during completion operations will maximize the knowledge on the fracture behavior allowing maximizing the learning curve on production improvements. Constant fluid sampling and detailed fluid analysis will improve the understanding on the geological model of the Achimov and, most importantly, is necessary for production allocation and the optimization of the entire asset – upstream and downstream.

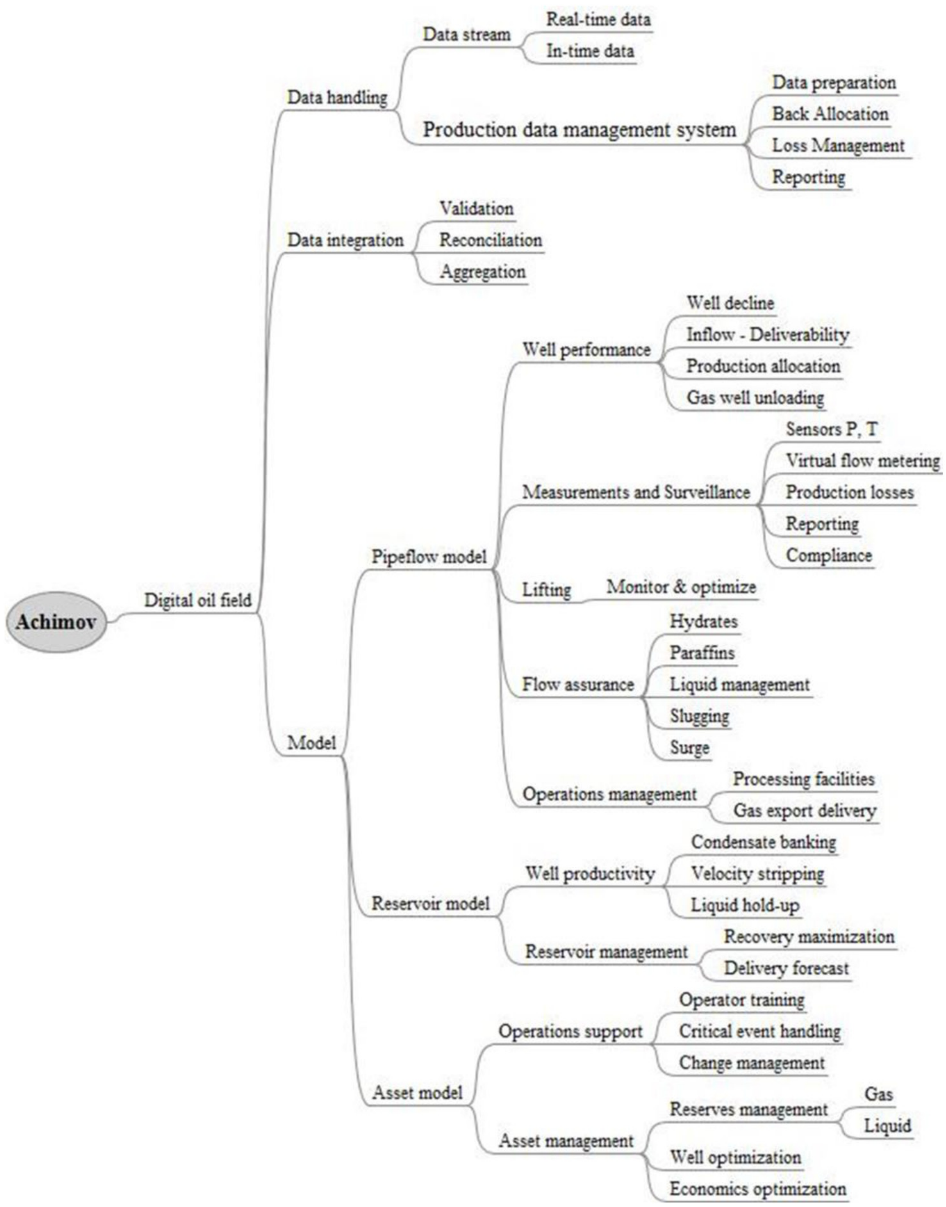


Figure 14—The solution modules of the digital oil field to achieve data consistency and to support the decision-making process on field development level

One of the key technical solutions for the well construction is the engineering of the mud system. Latest mud technologies use specially treated micronized weighting agents for non-aqueous or water-based applications. The mud components can be engineered to perform optimum for tight sandstones in a way to minimize invasion, do not change the wettability and keep their consistency and composition always constant. Modern mud systems are also engineered to operational activities reducing ECD losses, increase flow rates and reduced pump pressures for the same ECD, and reduce swab, surge, break circulation pressures.

It has been proven that maximizing the production rate and the recovery for tight reservoirs comes together with maximizing the reservoir exposure of the wellbore. Here, the completion technology is the key for maximum well performance. Pulsed hydraulic fracturing has been proven as the most efficient stimulation techniques in tight reservoirs and is standard nowadays in oil and gas shale development world-wide. The advantage of this specialized fracturing technique is that the fractures itself act infinite

Table 3—Summary of the three different well completion strategies

	Vertical wells	Horizontals wells	MRC wells
Gas recovery*	$<$ 40%	46 – 57%	50 – 62%
Oil recovery*	11 – 15%	12 – 16%	14 – 16%
Connects the reservoir	✗	✓	✓✓
Change in well construction strategy necessary	✗	⇔	✓
Well costs	$	$$	$$$$
Development costs	$$$	$$	$$
Initial risk	⇔	⇑	⇑⇑
Mitigated and prevented risk	⇔	⇑	⇑
Financial reward*	⇓	⇑⇑	⇑⇑

*after 10 years

acting through their channel system avoiding unnecessary pressure drop within the fracture. Any pressure drop applied to the wellbore is immediately transmitted to the fracture so that the wellbore can operate at a higher bottom-hole pressure with the same production – a mechanism to mitigate or postpone condensate banking around the wellbore. Moreover, once below the dew point the channels in the fractures transport the dropped-out liquid in the fracture better with limited pressure losses compared to conventional hydraulic fracture. The efficient placement of those fractures is also important as the initiation of several fractures might be overly time consuming. Modern (and proven) technologies use ball-drop systems that allow the instigation of subsequent multiple fractures in different parts of the horizontal wellbore in one operation. These specialized stage-fracturing systems reduce the overall completion time and risk but also maximize the impact of cleanup procedures to establish hydrocarbon flow better. Maximum production from the Achimov will depend on the combination of modern fracturing technologies and multi-stage completion. Please note that first successful applications of this technology have been already carried out and are evaluated for field-wide application (Yudin et al.)

The digital oil field

The main production challenges of the Achimov field are the large uncertainties that influence the gas and liquid recoveries and the poorly understood well productivities. This is mainly because of the limited amount of consistent data available on rock and fluid properties and the geological environment. The measured CGR is scattered throughout the field indicating strong compartmentalization. Well tests and production tests are contradicting for pressure measurements and fluid compositions. Different fluid gradients exist within productive units that indicate in some regions of the Achimov the presence of oil-rims. The reservoir models, which the operators maintain and are used for field development planning, capture insufficiently the reservoir physics. Condensate banking, non-Darcy flow and velocity stripping are poorly understood and many times not explicitly modeled. This results in poor forecasting and decision-making capabilities. Reservoir or asset management is therefore impracticable. However, it has been demonstrated that production optimization for the liquid phase alone (it is referred to the discussion on Figure 10) will be from utmost importance for an economically successful development of the Achimov.

It would be unrealistic (and possibly uneconomic) to assume that Achimov operators would significantly change their data gathering strategies to overcome all the above challenges. However, it is possible with vertical and horizontal integration reservoir and production processes to achieve a higher level of data consistencies with the models at-hand. The confidence in the decision-making process can be significantly improved through the update with newly available data, calibration and iteration of the various models. The combination and amalgamation of those models will allow reconciling, for example, PVT and rock properties so that over time optimum production and reservoir management strategies can be devised. Again, the fundamental part here is to establishing the learning curve.

Figure 14 depicts the various solution modules applicable for the Achimov gas-condensate field covering the evolution from the data stream to the asset model. This integrated field management process covers the handling of measurements, the surveillance, the interpretation of the data and the optimization of production rates and recoveries. It can be used as the decision support system for all operational levels. The asset model – or the "live" model – can be used for field development planning exercises and detailed economic analysis. This process is commonly referred to as the digital oil field.

Conclusions

It has been demonstrated that stage-fractured horizontal and maximum reservoir contact wells for the tight Achimov gas-condensate field are superior to vertical wells. Horizontal wells will produce at higher production rates; they will maximize the gas and liquid recovery; and they are overall more cost efficient. Table 3 depicts a brief summary of the benefits of all well types. Challenges that might jeopardize the construction of those wells can be mitigated with vertical and horizontal integration of the various technical and operational domains. In fact, entire solution paths from well construction to applicable technologies and to reservoir management strategies have been formulated. Central point in all strategies is to establishing the learning curve and increasing the confidence in the decision-making process.

The suggested methods are part of modern field development planning that postulates that every well is an appraisal well that drives the field development (data driven). For economic reasons, new or latest technologies should be rapidly trialed with the goal to evolve them to the optimum solution for the challenges at-hand or discard them (technology driven). And, most importantly, knowledge has to evolve during the development progress (decision driven). First, this is achieved byan agile and dynamic field development plan that can consider changes as the knowledge on the challenges increases. Second, a "live model" that is updated as soon as new information and data becomes available and queried for the optimum scenarios. And, secondly, a "live model" that is updated as soon as new information and data becomes available and queried for the optimum scenarios. This live model acts as a data and knowledge storage at the same time.

It is proposed to develop the Achimov reservoir on a step-by-step basis that follows the learning curve on the field development strategy. Utilizing proven technologies and processes horizontal wells should be drilled with an increasing complexity and pushing preconceived constraints. There are strong engineering indications that the cutting edge technology of MRC has the highest economic impact on the Achimov development; however, the evolution of the drilling and completion strategy will show that. Operators with their sub-contractors only need to ensure the growth of the learning curve.

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